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Degree of soil compactness is highly correlated with the soil physical quality index *S*

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ABSTRACT

The soil physical parameter *S* (*S*-value or *S*-index) has been proposed as an index of soil physical quality. Soil physical quality is negatively affected by soil compaction (e.g. caused by agricultural field traffic). It has previously been shown that *S* decreases with increasing soil bulk density. This study investigated whether the relationship between *S* and soil compactness can be described by a single function that is valid across soil textures when soil compactness is expressed in terms of the degree of compactness (*DC*), which is relative density expressed as the ratio of bulk density to a reference density. This would provide an alternative measurement for soil physical quality that is more easily obtained than *S*. We also evaluated different methods for deriving reference density and tested whether reference values for *S* suggested in previous studies correspond to critical levels of *DC* reported in the literature. The relationships between *S* and *DC* were investigated for the 12 FAO/USDA soil textural classes based on pedo-transfer functions, and compared with data reported in the literature. A strong positive correlation was found between *DC* and ln (1/*S*), and a unique function was found between *S* and *DC* that is valid across soil textures, with the possible exception of poorly sorted soils with a high sand or silt concentration. Experimental data on *S* obtained from the literature supported these findings. The reference value of *S* (0.035) previously proposed as a boundary between good and poor soil physical conditions was found to agree well with the level of *DC* (87%) reported in the literature as critical with respect to plant growth. Proctor density was found to be the most useful measure of reference density, better than Håkansson reference density, which introduced some texture dependency into the relationship between *S* and *DC*. Our findings indicate that 1/*S* is a good measure of soil compactness and support the usefulness of *S* as a soil physical quality index. However, our findings suggest that *DC* can also be used as an index of soil physical quality, and is much easier to obtain than *S*.

1. Introduction

Soil physical quality is the ability of a given soil to meet plant and ecosystem requirements for water, aeration and strength over time, and to resist and recover from processes that might diminish that ability (McKenzie et al., 2014). The soil physical quality is strongly affected by soil management including crops, fertilization, tillage, agricultural machinery traffic and drainage (e.g. Ball et al., 1997; Bronick and Lal, 2005; Kibblewhite et al., 2008 and Valipour, 2014). Some of the most important indicators of soil physical quality are relative field capacity, plant-available water capacity, air capacity, macroporosity, bulk density, organic carbon concentration and structural stability index, as they quantify (directly or indirectly) the ability of soil to store and provide the water, air and nutrients needed by crops (Reynolds et al., 2009). Poor soil physical quality can be evident in different ways, e.g. by poor water infiltration, surface run-off, hard-setting, poor aeration, poor rootability and poor workability, while a soil is believed to be in good physical condition if it shows the opposite or the absence of the conditions listed above (Dexter, 2004a). These conditions are not necessarily independent, since e.g. poor water infiltration is also strongly related to poor soil rootability.

Definition of a single index for soil physical quality has been the subject of much study by soil scientists. An appropriate index for soil physical quality must provide a texture-independent and comparable measure even when some of the conditions

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mentioned above occur together, i.e. it should reflect the resulting effects on soil physical quality in a meaningful manner. Dexter (2004a,b c) introduced the *S*-value or *S*-index as an index of soil physical quality, where *S* is the slope of the water retention curve (WRC) at the inflection point when logarithm (ln) of water suction (h) is plotted against gravimetric water content (θ_g), as shown in Fig. 1.

The WRC can be described by a range of mathematical functions, of which the van Genuchten (1980) equation is the most widely used and was originally used by Dexter (2004a) to develop his *S*-value theory. An advantage of the van Genuchten equation is that pedo-transfer functions (ptfs) based on large data sets are available for estimating the van Genuchten parameters (e.g. Wösten et al., 1999), while comparable ptfs are not readily available for other WRC functions that allow the effects of several factors on soil physical quality to be investigated (Dexter, 2004c). The van Genuchten equation is expressed as:

$$\theta_g = (\theta_{sat} - \theta_{res})[1 + (\alpha h)^n]^{-m} + \theta_{res} \tag{1}$$

where θ_g (kg kg^{-1}) is the gravimetric water content, θ_{sat} (kg kg^{-1}) and θ_{res} (kg kg^{-1}) are the saturated and residual water content, respectively, h (hPa) is the pore water suction (i.e. the negative of the matric water potential), α (hPa^{-1}) is a reciprocal suction that is characteristic for the soil, and m and n are dimensionless variables that describe the shape of the curve. The m and n variables are typically related by the Mualem (1976) constraint:

$$m = 1 - \frac{1}{n} \tag{2}$$

From Eq. (1), the slope of WRC at its inflection point is calculated as (Dexter, 2004a):

$$S = n(\theta_{sat} - \theta_{res})\left[1 + \frac{1}{m}\right]^{-(1+m)} \tag{3}$$

A number of experimental studies by Dexter and co-workers (Dexter, 2004a,b,c; Keller et al., 2007; Li et al., 2011) show that given values of *S* appear to have the same physical meaning across different soil textures. Dexter (2004a,b,c) suggested that *S* can be used as an index of soil physical quality that enables different soils and the effects of different management treatments and conditions

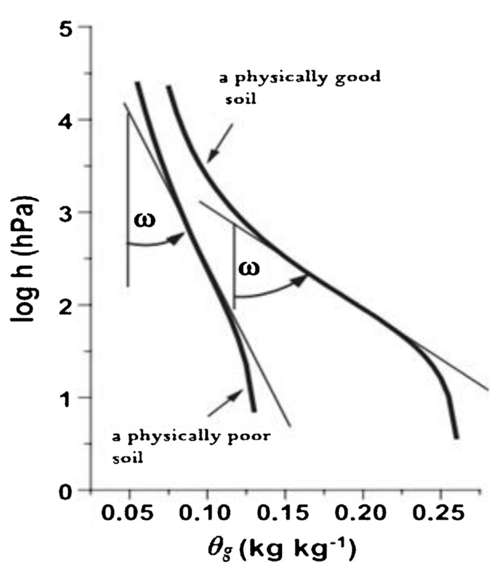

Fig. 1. Example of soil water retention curves showing the inflection point and the slope, tan ω, of the tangent to the curve at the inflection point for physically good and poor soils. θ_g and h are the gravimetric water content and pore water suction, respectively. From Dexter (2004a).

to be directly compared. Furthermore, Dexter (2004c) suggested a value of approximately $S = 0.035$ as the boundary between soils with good and poor soil structural quality and associated soils with $S < 0.02$ with very poor soil physical quality. For example, it was observed that root growth ceased at around $S = 0.02$.

Soil compaction caused by agricultural vehicular traffic is one of the major threats to soil productivity and functioning in modern mechanised agriculture. Soil compaction modifies the soil pore architecture, with negative impacts on a wide range of soil functions, and therefore reduces the physical quality of soil. Most physical, chemical and biological soil properties and processes are affected by the compactness of a soil. Consequently, the value of *S* decreases with increasing soil bulk density (Dexter, 2004a).

It is well known that bulk density as a component of soil physical quality is not an appropriate indicator for comparisons across soil textures. This is because a bulk density value that indicates a compact state in one soil (e.g. a clay soil) may indicate a loose state in another (e.g. a sandy soil) (Håkansson, 1990). For example, the yield response of different crops to compaction in different soils cannot be well characterised based on bulk density, because optimum and critical limits of bulk density for crop growth strongly depend upon soil texture. Comparisons of the compactness of soils across different soil textures require the use of relative (or normalised) density, which can be obtained by relating the (actual) bulk density to a reference bulk density. Several forms of relative density have been proposed and several methods for obtaining the reference density have been suggested. For instance, Håkansson (1990) introduced degree of compactness (*DC*), which is defined as:

$$DC = \frac{\rho_d}{\rho_{ref}} \times 100 \tag{4}$$

where *DC* is in%, ρ_d is the (field) dry bulk density and ρ_{ref} is the reference dry bulk density of the same soil. Håkansson (1990) obtained the reference density by confined, drained uniaxial compression of disturbed loose soil in a large oedometer cell (350 mm diameter, 120 mm height) at a stress level of 200 kPa and with a loading time of about one week. The 200 kPa was intended to represent a typical stress induced by agricultural vehicles, the compression method was designed to yield reproducible reference densities and the test was considered to be simple. While acknowledging the value of the Håkansson compression test from an agronomic point of view, this test is laborious and requires specialist apparatus that is not available in most laboratories, so a simpler standard test would be preferable.

Like *S*,*DC* is a texture-independent indicator of soil physical state. The *DC* value has been found to be a "high-level integrating parameter for soil physical quality" (Topp et al., 1997). The results of numerous long-term field experiments on mineral soils of Sweden have shown that the maximum yield of barley is obtained at a *DC* value of 87%, called the "optimum *DC*", and critical limits of penetration resistance (3 MPa) and air-filled porosity (10%, v/v) have been found at *DC* values of approximately 85–90% (i.e. $DC = 87\%$ on average) (Håkansson, 1990; Håkansson and Lipiec, 2000; Lipiec and Håkansson, 2000). Nevertheless, it must be noted that *DC* is a bulk property. For example, two soils with a given *DC* could have different structures and thus different qualities. However, on average, higher soil compactness is generally associated with poorer soil physical quality in the field.The degree of compactness has been primarily related to crop performance and used in studies with an agronomic focus. To the best of our knowledge, *DC* has not been directly linked to measures of soil physical quality such as the *S*-value. The aim of the present study was thus to investigate i) whether the relationship between *S* and soil compactness can be described by a single function that is valid